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Title: Temperature Rise in a Copper Wire During a High Current Pulse

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Temperature Rise in a Copper Wire During a High Current Pulse

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1. Introduction

The quench heaters to be used in the magnets to be built for the LHC project require the use of an external pulse type current source to quickly heat a stainless steel strip heater. The current pulse to be used for this purpose is a decaying exponential, with a peak current of 75 A and a time constant of 100 ms.

The wires used to conduct this pulse have conflicting requirements. The high currents require a conductor of a large cross section for safety margin, while the axial heat conduction in the copper wire dictates the use of the smallest practical conductor to minimize the heat load. This note describes the results of numerical calculations done to get a feel for the impact of the conductor sizing on the temperature rise of the wire at the end of the pulse.

2. The Numerical Model

The model calculates the temperature rise in a small time interval by calculating the energy deposited by the current pulse and the heat capacity of the wire. Several assumptions were made to keep the calculations as simple as possible. These are described in the following:

1. Heat flow out of the conductor was neglected. This amounts to a worst case temperature calculation, since in reality it is expected that the helium within the stranding of the wire, and insulation heat capacity would reduce the final temperature somewhat.
2. The calculations assumed the physical properties, such as temperature, of the wire to be uniform along the length, with no end effects. Thus, there is no axial conduction of heat in this model. In practice, there could be a temperature gradient along the length of the wire. Since more heat is generated in a warmer region due to higher resistivity, such gradients are likely to reduce the peak temperature.
3. Solder joints are not included.
4. Variation of the current profile resulting from an increase of wire resistance with time (due to temperature rise) are neglected. The current is thus assumed to follow a simple exponential decay. Since the actual current pulse is likely to be stretched due to this effect, the calculations are done for a time constant of 200 ms, instead of 100 ms.

3. Calculation Details

With the simplifying assumptions made as above, the problem reduces to simply calculating the amount of energy deposited in a small time interval, and calculating the resulting temperature rise, based on the physical properties of copper. Because both the heat capacity and resistivity of copper change approximately three orders of magnitude between 4K and room temperature (see Fig. 1), it was necessary to include this variation in the calculations. A linear interpolation was used for temperatures lying between two data points in Fig. 1.

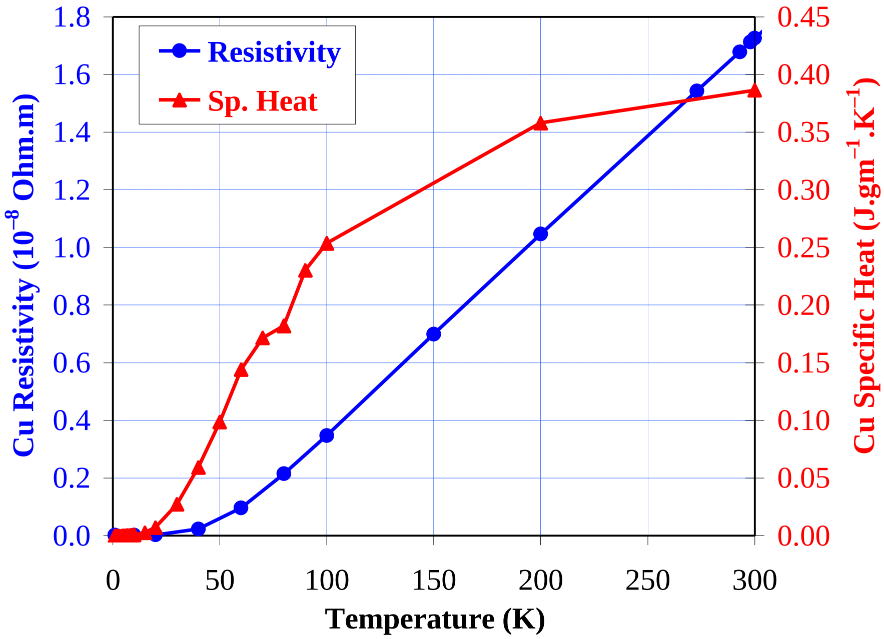

Fig. 1 Electrical resistivity [1] and specific heat [2] of copper as a function of temperature.

The current pulse is described by:

$$I(t) = I_0 \exp(-t/t) \tag{1}$$

where I_0 is the peak current at time $t = 0$ and t is the time constant. The energy, ΔE, deposited into a unit length of the wire in a time interval between t and $t + \Delta t$ is given by:

$$\Delta E = R(t)\int_{t}^{t+\Delta t} I^2(t)dt = I^2(t)\, r(t)\left(\frac{4}{p\, d^2}\right)\left(\frac{t}{2}\right)\left[1 - \exp(-2\Delta t/t)\right] \tag{2}$$

where $R(t)$ is the resistance per unit length of the wire at time t, which in turn depends on the temperature, $T(t)$ at time t, the diameter, d, of the wire and the electrical resistivity, r. In writing Eq. (2), it has been assumed that the change in temperature during the interval Δt is small enough that the resistance can be treated as a constant over this duration. However, it is not required that this interval be also small compared to the time constant of the current pulse. If ΔT is the temperature rise caused by this energy, the temperature at time $t + \Delta t$ is given by

$$T(t+\Delta t) = T(t) + \Delta T = T(t) + \frac{4\Delta E}{p\, d^2 r_m C(T)} \tag{3}$$

where r_m is the mass density and C is the specific heat of copper.

Starting with a given initial temperature, $T(0)$, the temperature profile can be calculated using Eqs. (1)-(3). For temperatures near 4 K, the heat capacity of copper is exceedingly small. To ensure the validity of Eq. (2), the time increment must be chosen to be small enough to keep the temperature rise reasonably small. The calculations used a variable time increment which was adjusted to always yield a fixed amount of temperature rise, arbitrarily chosen to be

0.1 K. Reducing the temperature rise step to 0.05 K had negligible effect on the calculated temperature profile. Using Eqs. (2) and (3), it can be shown that the time increment, Δt, needed to obtain a specified temperature increment, ΔT, is given by

$$\Delta t = -\frac{t}{2}\ln(1-x); \quad \text{where} \quad x = \frac{2(p\, d^2/4)^2\, r_m\, C(T)\,\Delta T}{I^2(t)\; r(T)\, t} \tag{4}$$

Initially, when the current is high and the specific heat is low, the time step required for a given temperature rise is very small (a few microseconds for 0.1 K). As time progresses, the current reduces and the specific heat increases, allowing one to use longer time steps. Obviously, one can not keep using Eq. (4) with a fixed ΔT for all times, because once several time constants have elapsed, the temperature will be practically constant with time and one can no longer force a fixed value of ΔT. This happens when the parameter ξ in Eq. (4) becomes 1 or more. In the present work, this was avoided by specifying a maximum size for the time step, arbitrarily chosen to be 0.2 s, although a much longer time step could have been chosen without any loss of accuracy. It should be noted that an exact analytical expression for energy in Eq. (2) allows us to use an arbitrarily large time step, as long as the physical properties do not change significantly. The calculations are continued until there is no appreciable change in temperature with time (typically up to $t = 10t$).

4. Results

Calculations were performed as described in the previous section for 0.2 s time constant current pulses. Calculations were done for various values of peak current and initial temperature for wire diameters of 15.94 mils (26 AWG) and 20.10 mils (24 AWG). Typical temperature profiles are shown in Fig. 2 for the parameters listed in the figure. The steady state temperature is 43.5 K for the 26 AWG wire and is 25.2 K for the 24 AWG wire. The current profile, and the resulting voltage profiles for both the wire gauges are shown in Fig. 3. The interplay of decaying current and non-linear variation of resistivity and specific heat

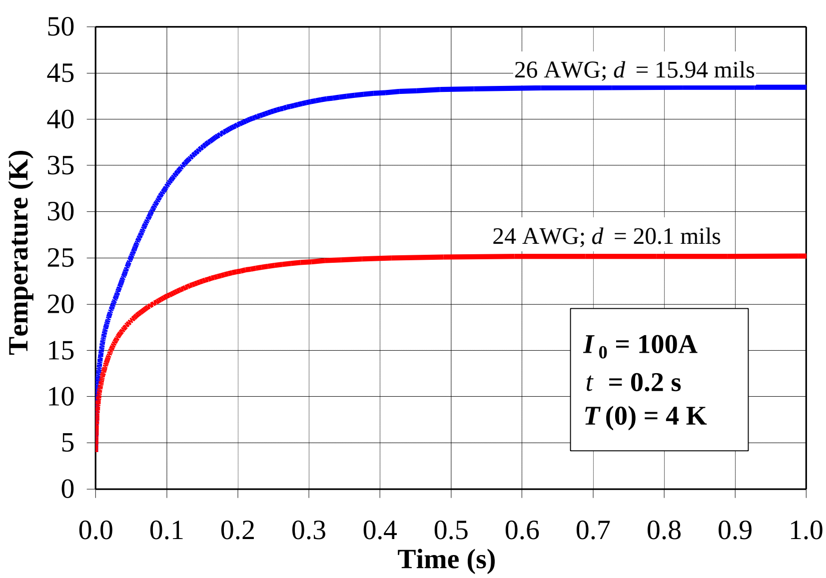

Fig. 2 Typical temperature profiles for a 100 A, 0.2 s pulse and 4 K initial temperature.

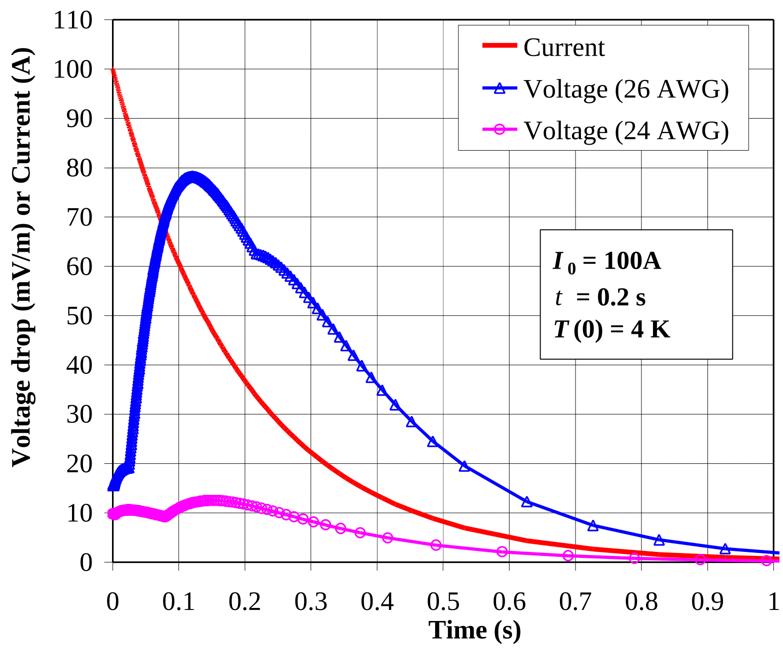

Fig. 3 Current and voltage profiles for a 100 A, 0.2 s pulse and 4 K initial temperature.

results in interesting voltage profiles. The peak voltage drop is 78.3 mV/m for the 26 AWG and 12.5 mV/m for the 24 AWG wire.

The final temperature as a function of peak current is shown in Fig. 4 for initial wire temperature of 4 K. Due to highly non-linear dependence of physical properties on temperature, the final temperature is strongly dependent on the initial temperature. Fig. 5 and Fig. 6 give the variation of final temperature and the peak voltage with the initial temperature. It can be seen that the final temperature is below room temperature for initial temperatures as high as 100 K. However, the resistance becomes high enough that the peak voltages required to sustain the current pulse may become prohibitive (see Fig. 6).

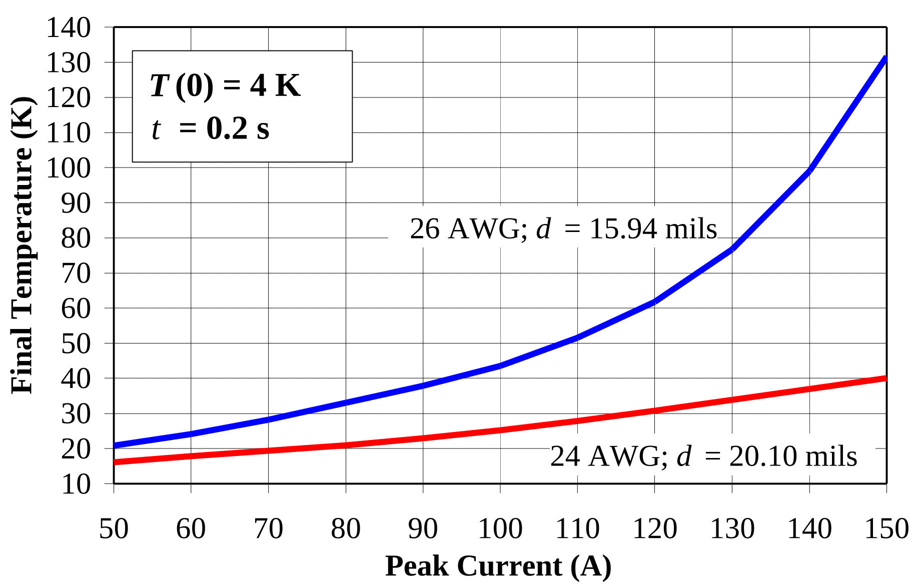

Fig. 4 Final temperature as a function of peak current.

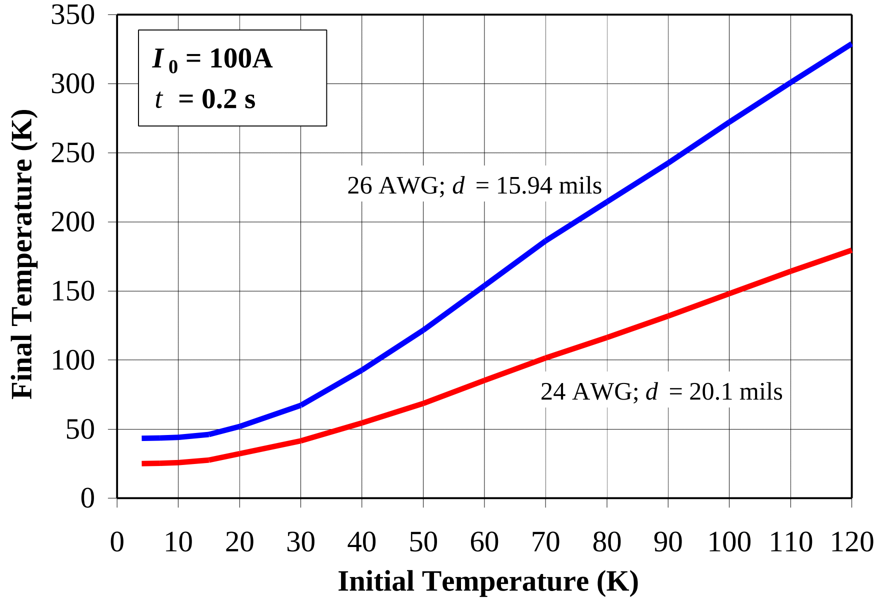

Fig. 5 Steady state temperature as a function of initial temperature.

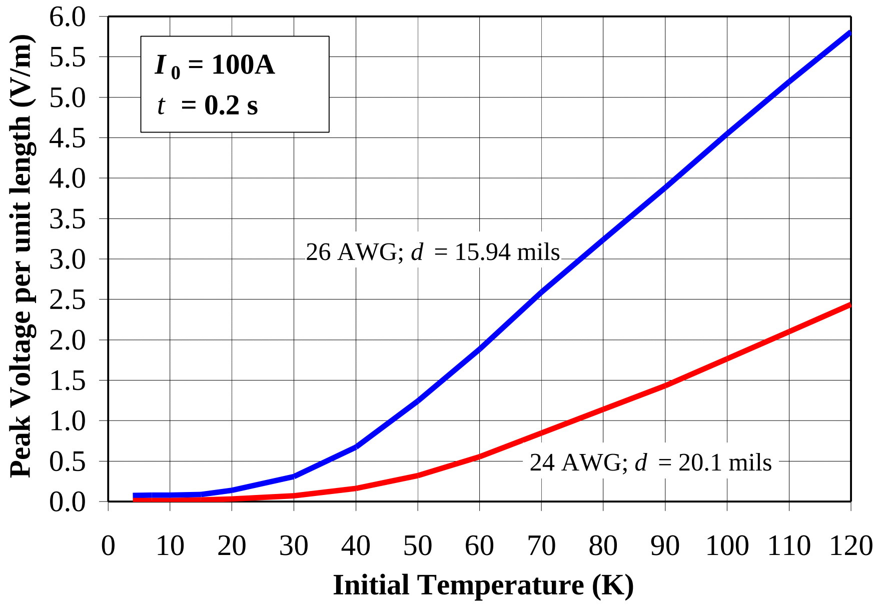

Fig. 6 Peak voltage per unit length as a function of initial temperature.

5. Conclusions

From the results presented in this note, the proposed AWG 26 wire is capable of operation with a 0.2 s time constant, 100 A current pulse, with the peak wire temperature well below 50 K, provided the initial temperature of the wire is at 4 K all along its length. The actual current proposed to be used is 75 A with a 0.1 s time constant. Many heat transfer modes are neglected in this work, and the present calculations are expected to represent a worst case scenario. On the other hand, presence of any impurities in copper may severely influence the low temperature properties.

The results also show that the voltage drop per unit length of the wire is small, with the peak voltage drop less than 80 mV/m for 26 AWG wire and an initial temperature of 4 K. The voltage drop and final temperature are relatively insensitive to the starting temperature below ~20 K, but both rise rapidly for starting temperatures above this value. Thus, care must be taken in designing the cold to warm transition, such that the temperature of the wire is maintained below ~20 K throughout its length. A wire gauge thicker than 24 AWG may have to be used if this condition on the initial temperature can not be met. As an example, Fig. 7 shows the final temperature and peak voltage as a function of wire gauge when the initial temperature is 100 K (solid lines) or 300 K (dashed lines). Such a figure could be used to select the appropriate wire gauge in these cases. Thermally anchoring the wire at a suitable lower temperature (~50 K, say) can help in achieving safe operation with much thinner wire and a reduced heat load.

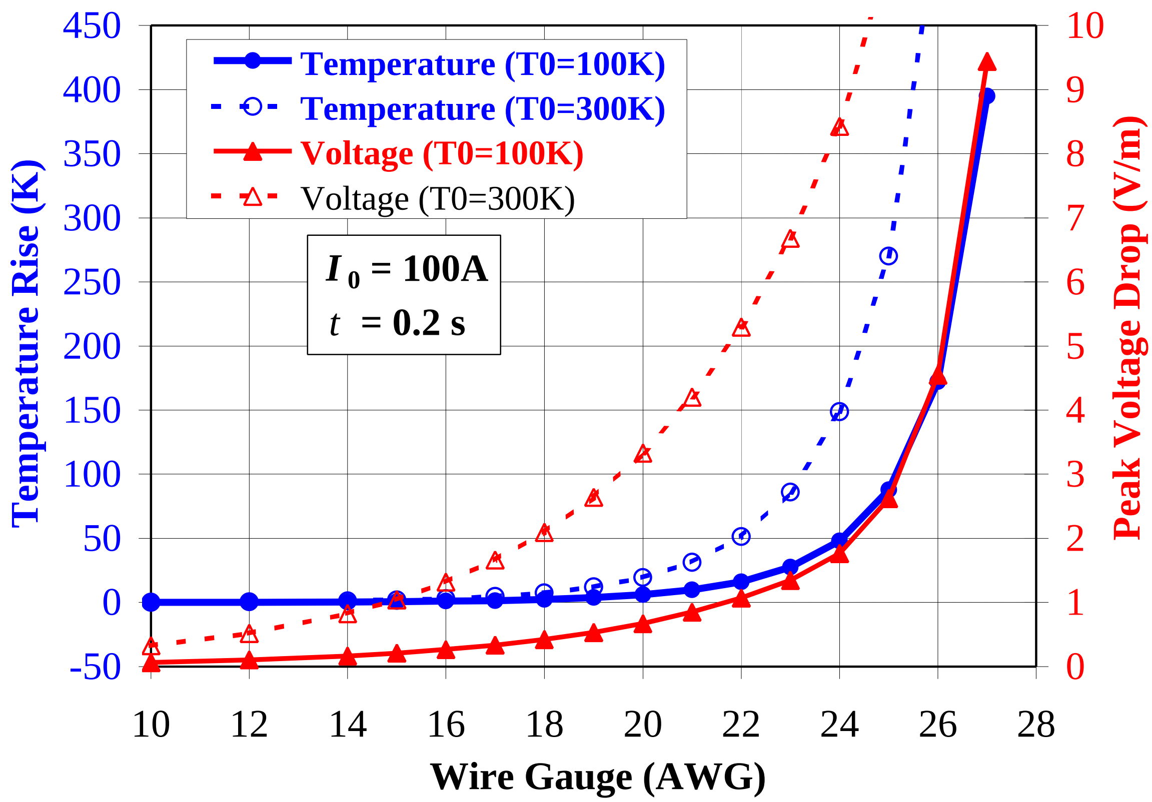

Fig. 7 Temperature rise and peak voltage per unit length as a function of wire gauge.

6. References

[1] *CRC Handbook of Chemistry and Physics*, D. R. Lide, Ed.,73rd edition, CRC Press,1992, p. 12-34.

[2] *Selected Cryogenic Data Notebook*, Vol. I, Sec. VIII, BNL 10200-R, Brookhaven National Laboratory, August 1980.